Deep Space Optical Communications

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ABSTRACT

The future demand for enhanced telecommunication capacity required to support human and robotic exploration from deep-space has motivated the advancement of free-space laser communication technologies for the past few decades. Steady advances in these technologies, validated through space-to-ground demonstrations, have resulted in incremental advances with the deep-space optical communications (DSOC) technology demonstration being one of the next milestones on NASA's roadmap. NASA's Psyche Mission to launch early next decade plans to host a DSOC flight laser transceiver for link demonstrations extending from 0.1 to farther than 2 astronomical units (AU). The capabilities validated though this demonstration, we expect, could spur the use of optical communications infrastructure around Mars in the next few decades. In this paper we summarize ongoing activities underway at the Jet Propulsion Laboratory in preparation for the DSOC technology demonstration and go on to present discussions on the drivers for developing a robust deep space laser communications operational capability.
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Keywords: Laser communications, deep-space, photon-counting, optical ground antennae

1. INTRODUCTION

The future demand for enhanced telecommunication capacity required to support human and robotic exploration from deep-space is spurring the advancement of deep space telecommunications which includes the augmentation achievable with optical communications. Partially validated advances in these technologies through space-to-ground demonstrations have resulted in readiness for NASA's Deep Space Optical Communication (DSOC) Project technology demonstration [1]. The baseline payload for NASA's Psyche Mission (planned to launch around August of 2022) includes hosting the DSOC flight laser transceiver (FLT) for a link demonstrations spanning ranges of approximately 0.1-2 astronomical units (AU). Likewise, ESA is planning a Deep-Space Optical Communications System (DOCS) technology demonstration from the Sun-Earth Lagrange (L5) point, hosted by their Space Weather Mission spacecraft [2]. The capabilities validated through these demonstrations, we expect, could feed infusion into future operational systems around Mars by the end of the next decade, thereby enabling support of higher resolution science and human exploration. Future deep space missions to farther ranges would also benefit from these developments.

In this paper we present a status summary of the DSOC technology demonstration followed by discussions of future developments drivers for achieving the desired operational capability to augment NASA's deep space telecommunication services.

The paper is organized as follows. In Section 2 a brief summary of the planned DSOC Project operations, system description and performance is presented. In Section 3 discussions addressing follow-on flight sub-system developments for operational infusion is presented. Section 4 discusses ground development drivers and status. In Section 5 presents the conclusions.

2. THE DSOC TECHNOLOGY DEMONSTRATION

2.1 Background and Objectives

Laser communications from deep space ranges conceived shortly after the invention of the laser was first seriously addressed by NASA through the Mars Laser Communication Demonstration (MLCD) Project [3] which was aborted due to the cancellation of the host spacecraft called the Mars Telecommunications Orbiter. Since then the Lunar Laser

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Communication Demonstration (LLCD) [4], the farthest successful demonstration to date, was completed in 2013. The DSOC effort was preceded by the Deep-Space Optical Terminals (DOT) [5] for flight, initiated around 2009. The DSOC Project continued technology advancement started by the DOT Project through 2016. In January of 2017, NASA selected the Psyche Mission for development as part of the Science Mission Directorate's Discovery Program. Hosting the DSOC technology demonstration by accommodating the FLT on the Psyche spacecraft [6] was included in the mission plan. The Psyche Mission science objectives [7] are to explore the asteroid Psyche-16 with an approximately 3-year cruise to the asteroid. The DSOC technology demonstration is planned during the early cruise and depending on health and status of the FLT, as well as, Psyche Mission resources may be extended.

The key objectives of the planned DSOC technology demonstration are (i) to validate the Consultative Committee for Space Data Systems (CCSDS) recommended [8] photon-counting receivers combined with high peak power laser transmitters that can operate efficiently at a few bits per detected photon; (ii) to demonstrate link acquisition/re-acquisition, tracking and laser beam pointing control needed for operating deep space links.

2.2 DSOC Operational Architecture and Link Conditions

The baseline DSOC beacon based operational architecture is shown in Figure 1. The system being developed consists of the following operation nodes: (i) the FLT on-board the Psyche mission spacecraft, capable of acquiring a 1064 nm uplink/beacon laser and transmitting a 1550 nm downlink laser; (ii) a Ground Laser Transmitter (GLT) transmitting a 1064 nm beacon with limited uplink data, located at the Optical Communication Telescope Laboratory, Table Mountain, CA; (iii) a Ground Laser Receiver (GLR) utilizing the Hale telescope at Palomar Mountain, CA, equipped with a photon-counting receiver; (iv) a Mission Operations Center for coordinating ground operations.

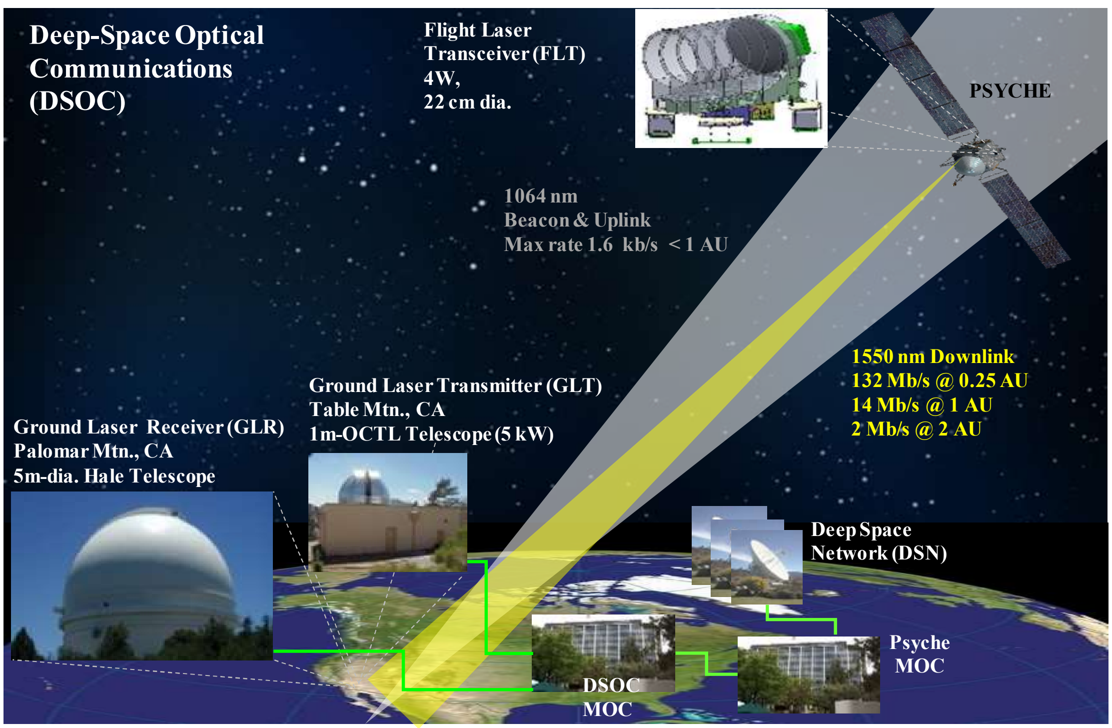


Figure 1. Planned DSOC operational architecture showing the four primary nodes: (i) FLT on-board the Psyche spacecraft; (ii) GLT; (ii) GLR; (iv) DSOC MOC along with the Psyche MOC and the DSN nodes that would support DSOC operations.

The ground nodes use existing assets for cost-effectiveness. The choice of non-co-located ground transmitter and receiver was made in order to avail a relatively large ground receiver collection area, with 5m diameter aperture, while easing optical transmit/receive isolation. A consequence of utilizing non-co-located ground transmit and receive nodes is that simultaneous cloud free line of sight (CFLOS) at both locations is mandated. On an average 54% availability [9] with seasonal variations is expected.

Figure 1 also shows Psyche Mission operational nodes which include the Psyche spacecraft with on-board resources and accommodation for the FLT, a mission operations center (MOC), and the Deep Space Network (DSN) for supporting primary Psyche Mission telecommunications including telemetry returned from the DSOC FLT.

A planned Mars flyby by the Psyche spacecraft, during the first year of cruise, imposes a 21-day launch window in August 2022. Figure 2 shows data derived from a notional Psyche spacecraft trajectory. A time series of the variation of range in astronomical units (AU), elevation angle (air-mass) with a 20-degree cutoff, and sun angles is shown with an August 16, 2022 00:00:00 epoch.

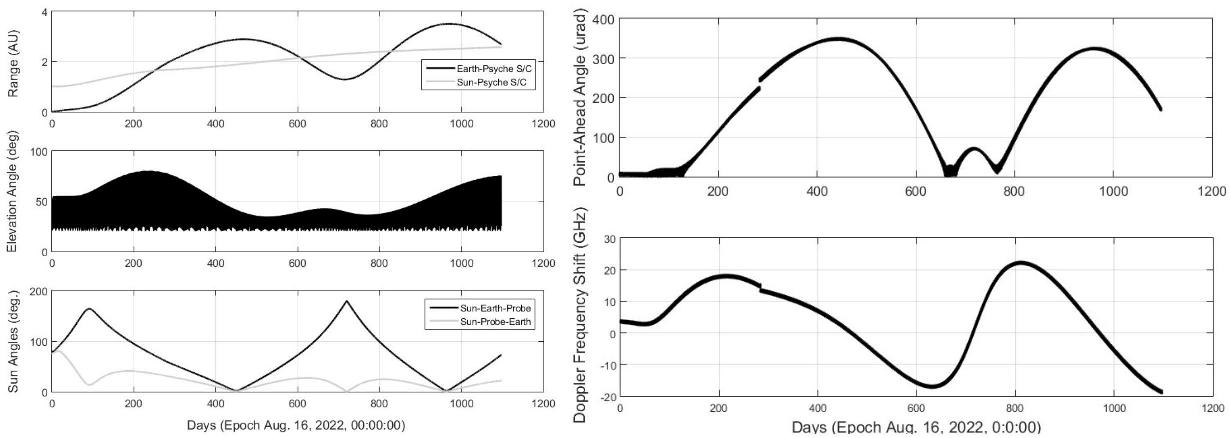


Figure 2. (a) Variation of distance (top panel), elevation angle (middle panel) with a 20-degree cut-off, sun angles (bottom panel) as a function of days from launch; (b) Point-ahead angle (top panel) and Doppler frequency shift @ 1550 nm (bottom panel).

Following 30-40 days of post-launch commissioning, link demonstrations would be to start at approximately 0.1 AU distance. Beyond 0.2 AU velocity (slope of range in upper left panel) changes more rapidly, approaching a distance of approximately 2.6 AU at the end of the first year. The primary DSOC technology demonstration is planned during the first year with approximately two contacts per month. For approximately the first 270 days at least 2-hour nighttime contacts can be supported. For the remainder of the year nighttime contacts incrementally decrease to 20-30 minutes. Link demonstrations with uplink only are also planned when the GLR cannot support daytime links because the sun-earth-probe (SEP) angles are too shallow. Following the first year of Psyche Mission cruise, assuming health and status of the DSOC FLT remains nominal and resources are available from Psyche spacecraft extended mission operations would be negotiated within the constraints of the downlink SEP and uplink beacon power that covers ranges out to 2.7 AU.

The spacecraft velocity relative to the ground can be decomposed into cross-range and range-rate (along the line-of-sight) components. The cross-range velocity translates to large point ahead angles (~300 μrad maximum) while the range rate contributes a maximum of ~ 70 parts per million (ppm) Doppler shifts. Figure 2b shows how these parameters vary over the mission duration. Implementation of the point ahead angle is critical since it is significantly larger than the FLT near diffraction limited beam-width.

A typical link would be initiated by the ground transmitting the beacon laser using time-stamped spacecraft position predicts, provided by the Psyche mission. The beacon beam-width is expected to cover the predict uncertainty. The FLT operates using pre-loaded scripts transmitted to the spacecraft in advance. At the designated time the FLT performs a scan to find the beacon signal within the pointing uncertainty of the spacecraft. The beacon signal is uniquely identified through its modulation. Temporally synchronizing to the beacon modulation allows immunity to background additive noise from Earth upwelling radiance and stray light from the sun, provided the pointing detector is not saturated. Additionally, limited uplink data (1.6 kb/s @ 1AU) can also be received. Following "lock" on the beacon signal the FLT updates the centroid estimates of the beacon and uses this as a pointing reference to compute the point-ahead angle and transmit downlink using on-board position, velocity and attitude knowledge. The ground receiver points to the spacecraft location using predicts and upon incidence of the downlink performs spatial and temporal acquisition in order to receive the communications. The field-of-view on the receiving telescope accommodates the predict uncertainty.

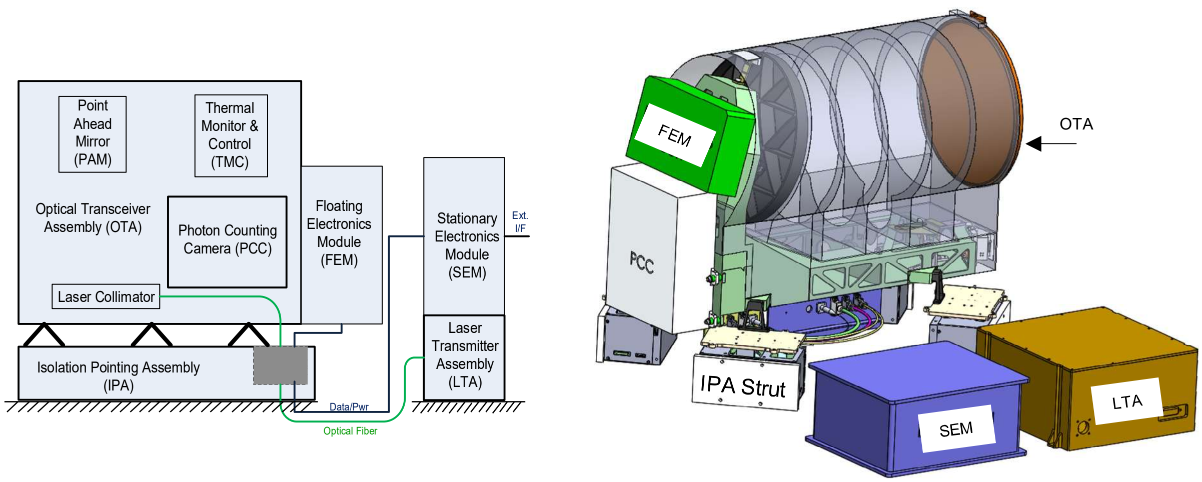
2.3 DSOC FLT

A simplified functional block diagram of the DSOC FLT is shown in Figure 3a. The FLT has a “floating” and “stationary” part. The elements “hard mounted” to the spacecraft platform comprise the stationary while parts decoupled from the spacecraft platform, as described below, are termed floating.

The optical transceiver assembly (OTA) houses the optics for receiving the laser beacon and transmitting the downlink laser. A detailed description of the optical design of the OTA was reported in reference [10]. The OTA has a photon counting camera (PCC) as a pointing detector for sensing the 1064 nm beacon at the receiving focal plane. The laser transmitter assembly (LTA), mounted separately as a stationary element, couples downlink laser signal to the OTA by means of an optical fiber. The downlink laser is collimated within the OTA and reflects off a point ahead mirror (PAM) so that it can be steered over an angular range that covers the point-ahead angle. The floating electronics module (FEM) is attached to the OTA assembly and functions as the pre-processor for the PCC readout and the PAM driver.

The OTA is mounted to an isolation pointing assembly (IPA) comprised of four struts. The base of each strut attaches to the spacecraft platform with a floating part that de-couples or “floats” the OTA (with PCC, FEM and PAM) thereby isolating it from base platform vibrational disturbance. The floating part of the FLT is connected to the stationary side through a low stiffness umbilical comprised of data/power lines and an optical fiber. The IPA isolates the OTA and its attachments from platform disturbance but also rejects disturbance that couples to the floating side through the soft cable/fiber attachment. The IPA control allows steering the OTA over a field-of-regard sufficient to allow acquisition of the beacon within the spacecraft body pointing uncertainty. The stationary electronics module (SEM) has a processor, digital electronics and power distribution for satisfying all the acquisition, tracking pointing and data transmit/receive signal processing. The SEM also interfaces to the spacecraft for exchanging operational command and telemetry.

Figure 3b shows a solid model rendering of the conceptual DSOC FLT. The optical head consisting of a stationary and floating part are mounted to the spacecraft platform and the LTA and SEM are separately attached to the spacecraft.



(a) (b)

Figure 3. (a) Simplified functional block diagram of the DSOC FLT; (b) Conceptual solid model rendering of the FLT

The FLT transmits 4 W average laser power through the unobscured 22 cm clear aperture.

2.4 DSOC Ground Data Systems

The DSOC Ground Data System (GDS) uses OCTL as the GLT. We are developing the laser transmitter and data formatter (for modulating the lasers) for installation at OCTL. Relay optics for coupling the laser output to the telescope optical train with an exit path through the primary mirror is planned. As in previous space demonstrations a multi-beam beacon laser is planned. Since average powers as high as 5 kW are planned for making contact to the spacecraft at ranges of 2.7 AU 10-beamlets or sub-aperture beams would be transmitted out of the 1m OCTL telescope. Using 10 beams provides averaging of the atmospheric turbulence induced irradiance fluctuations, or scintillation cause by thermally induced random refractive index variations.   This multi-beaming approach also allows achieving the high transmitter power by using lower power individual lasers that add up when overlapped in the far-field.

The GLR would be implemented by integrating a tungsten silicide (WSi) superconducting nanowire single photon detector (SNSPD) array of approximately 320 micrometer diameter at the focal plane of relay optics that guides light from the telescope focus. The relay optics includes an acquisition camera, a steering mirror and a spectral filter with noise equivalent bandwidth of approximately 0.17 nm. An operational constraint of the GLR disallows direct insolation of the telescope dome interior or structure. Limited daytime opportunities are expected within these constraints.

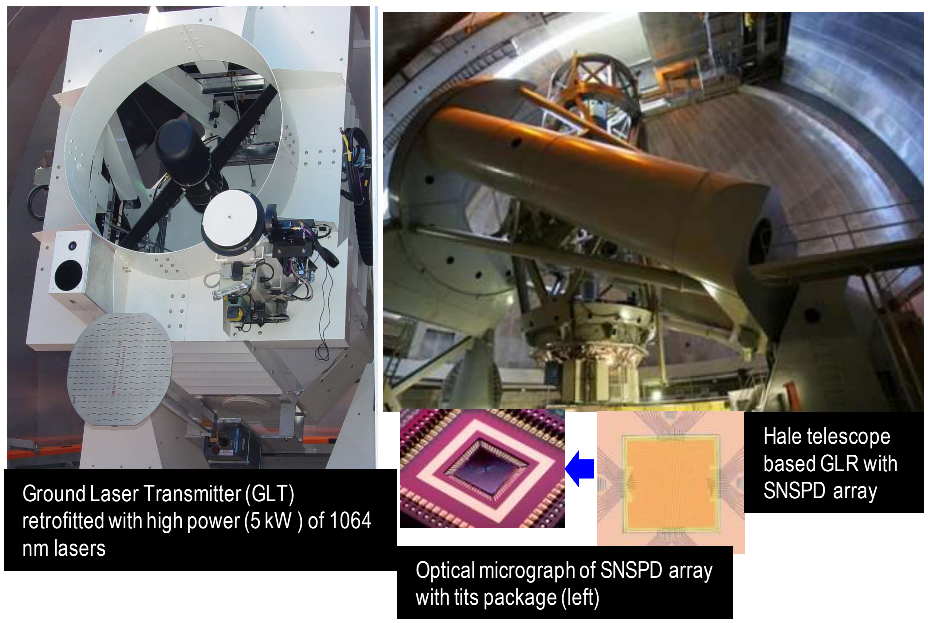


Figure 3. OCTL telescope to be used for the DSOC GLT (left) and Hale telescope to be used for GLR (right); an optical micrograph of the SNSPD array and the packaged detector are also shown.

2.5 Link Performance Summary

The DSOC System link performance under nominal atmospheric conditions and based on current best estimates of link parameters is shown in Figure 4 below.   A more detailed discussion of the link performance was reported in ref. 11. For the uplink data-rates of 1.6 kb/s are targeted for 1 AU distance. Beyond 1 AU the primary function of the beacon would be to provide a beacon for assisting acquisition and tracking on the FLT with a required mean irradiance at the aperture of approximately 4 picowatts/m^2.

2.6 End-to-end signaling verification testbed activity

The DSOC Project maintains active testbeds for advancing system design by verifying predicted performance of components, assemblies and end-to-end systems. Two parallel testbeds: (i) pointing and tracking control and (ii) end-to-end signaling have been developed.

The pointing and control testbed uses a prototype aluminum FLT integrated to the IPA and the PCC. Figure 5a shows the FLT in the testbed. In order to test pointing and tracking functions in the laboratory a gravity offload for suspending the assembly from its center of mass is used. This gravity offload is needed to test the IPA which cannot otherwise overcome gravity loading. A beacon to overfill the 22 cm aperture is generated from a laser test and evaluation station (LTES) in close proximity to the FLT (not shown). Overfilling the FLT entrance aperture with a collimated laser beam, best emulates the incident beacon wave-front on the FLT in space. The FLT can acquire and track this beacon and point a laser back that is received by sensors in the LTES.   Disturbance can be applied to the base of the IPA to test the isolation and rejection of vibration. This testbed has verified approximately 1-μrad rms tracking errors per axis with representative injected base disturbance.

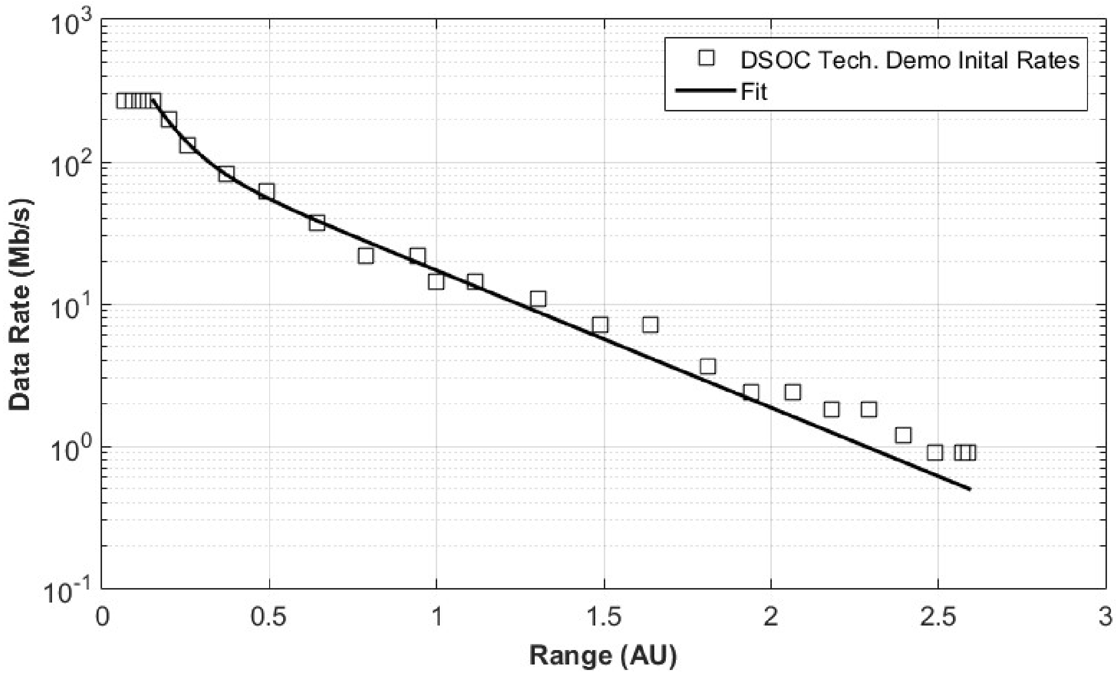


Figure 4. Estimated link performance for the DSOC system based on current best estimates of link parameters. The solid line fit is included as a visual aid.

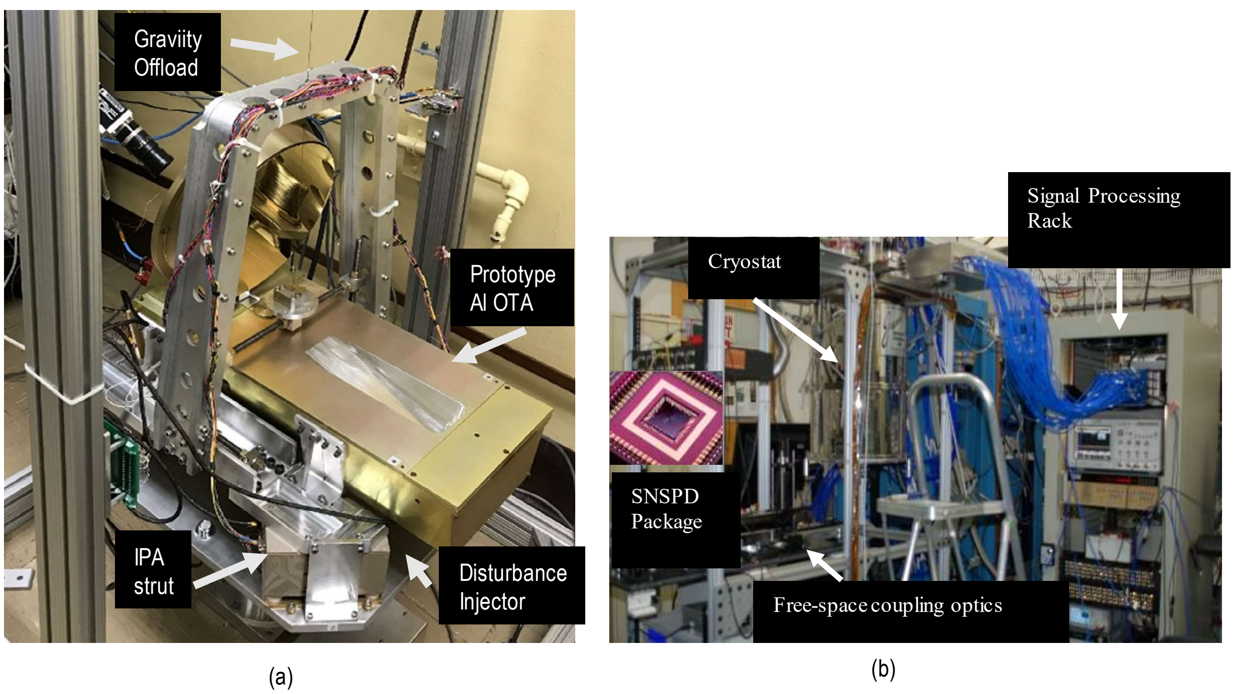


Figure 5. (a) Showing the prototype FLT based on an aluminum OTA integrated to a representative IPA and PCC with the capability of receiving a beacon while representative disturbance can be injected at the base; (b)

Figure 5b shows a photograph of the current testbed for signaling. This represents the current status toward the development of a ground photon-counting receiver [12] capable of demodulating the downlink optical signal over a wide dynamic range of operating conditions. The WSi SNSPD array is housed in the cryostat and held at ~ 1K with free-space optical access through a window. The waveform is generated using prototype SEM digital slice flight-like electronics and modulated on a 1550 nm fiber coupled test laser. The single mode optical fiber carries the optical signal from the flight sub-system laboratory to the location of the testbed shown in Figure 5b where the 1550 nm light is re-collimated and free-space coupled to the detector in the cryostat. The optical train for re-collimating the 1550 nm light includes the capability of injecting controlled amounts of background in order to run tests with representative signal and background incident on the detector. The detector readout has a 40K pre-conditioning stage followed by room temperature amplifiers outside the cryostat and 64 parallel signal streams are processed by a threshold comparator subsequently fed to a time-to-digital convertor (TDC) that records photon arrival timestamps to a file for software receiver post-processing. Ongoing and future improvements to the testbed include a programmable amplitude modulator in order to simulate channel fading, improved spectral filter components, and real-time streaming digital signal processing electronics.

Testing has been initiated with the testbed with constant input mean power levels and uniform background. Test cases that include PPM 16, 0.5 ns slot width and a code-rate of 0.66 corresponding to 267 Mb/s (highest data rate for DSOC FLT) and a few other anticipated operating points have been verified. The link budget predicted threshold number of photoelectrons per slot (k_s) with corresponding mean background photoelectrons per slot (k_b) were verified through laboratory measurement within the limits of calibration errors. The link margins used were also verified. A detailed description of these results is planned for future publication. Incorporating fading effects, Doppler shifts and a channel inter-leaver to mitigate fades are planned in future tests.

3. FUTURE FLIGHT SYSTEM NEEDS

Successful operation of the DSOC FLT would prove a significant milestone in NASA's quest for augmenting the state-of-art telecommunications from deep space. An architecture and operational procedure should be demonstrated and advanced in readiness for a follow-on operational demonstration. For infusion into NASA's future missions, longer term reliability and scaling considerations for enhanced performance need consideration.

A priority for near term infusion, following a DSOC technology demonstration, is likely to be an orbiting telecommunication infrastructure around Mars [13]. The likely emphasis would be on high rate data return to Earth stations to enable higher resolution mapping of Mars toward eventual support of human exploration.

Data-rate demands for these future optical links would likely require increasing the emitted isotropic radiated power (EIRP) for future FLT's. Based on past communication architectural studies [14] 50 cm aperture diameters and 20 W average power lasers are considered low risk. Analysis indicates that implementing this low risk modifications to increase EIRP may be adequate to satisfy the data-rate demands from Mars. In addition to scaling the EIRP relative to the DSOC FLT, a reliable and robust service from Mars orbiting assets would require the ability to operate while pointing close to the edge of the sun in order to preserve link availability. The DSOC FLT architecture was designed to operate down to 3° sun-probe-earth-angle (SPE) but ground asset limitations restrict demonstrating beacon acquisition at 5-10° SPE angles. Combining larger aperture diameters with low SPE operations would be addressed in the future.

As elaborated in ref. 11 optical system performance suffers degradation when operating at shallow sun angles. There are potential system-wide solutions for overcoming this degradation one of them of which is further increasing the EIRP by increasing the average laser power beyond 20W. Our analysis indicates achieving 50 W average power laser transmitters can mitigate the degradation. Possible ways of achieving the higher laser power could be implementing multiple wavelength channels for coarse multiplexing. Increasing optical flight transceiver EIRP would also go a long way toward servicing links farther out into space including the outer planets.

Recently, NASA has teamed with others to embark on a new set of studies [15] that address interstellar probes that can cover ranges of 5 -15 light-years (Ly). For this class of mission concepts, there would be an emerging need for orders of magnitude higher EIRP. As an example, recent studies indicate that communicating form inter-stellar ranges requires 4 kilowatts of average laser power and 2.5 m diameter aperture diameter. Transmitters for interstellar missions bring new challenges with Doppler shifts since the propulsion systems present relativistic velocities with correspondingly higher wavelength shifts. Research and development toward addressing these needs through a better understanding of requirements and potential design solutions are needed. Laser lifetime for supporting this class of missions also needs to be addressed.

To summarize this section, there appears to be a potential future need for ever-increasing EIRP flight transceivers with relatively low risk solutions in the near term (next two decades) with considerable development needed for longer term needs. Realizing the larger EIRP would also introduce tighter pointing requirements and innovations for thermal management, and modulation and encoding electronics for higher power transmitters. A beaconless solution for longer term farther range missions is also needed.

4. FUTURE GROUND SYSTEM NEEDS

Ground deficiencies for infusion toward operational mission capability are stark when viewed in the post-DSOC technology demonstration time frame. A ground infrastructure for receiving deep space laser communications signals does not exist today. Using astronomy assets for operations does not offer a viable or reliable solution. Studies have indicated potential cost risk associated with implementing this capability. A robust solution for this is still forthcoming but some recent and ongoing activity at JPL to try to bridge this gap is presented.

JPL has been considering RF-Optical Hybrid apertures that involve mounting mirrored surfaces to a fraction of existing 34 m radio frequency antennae in the NASA Deep Space Network (DSN). Initial studies and proof-of-concept experiments toward this [16, 17] has been completed and a detailed system engineering effort to better understand the implementation technologies and capabilities is now underway.

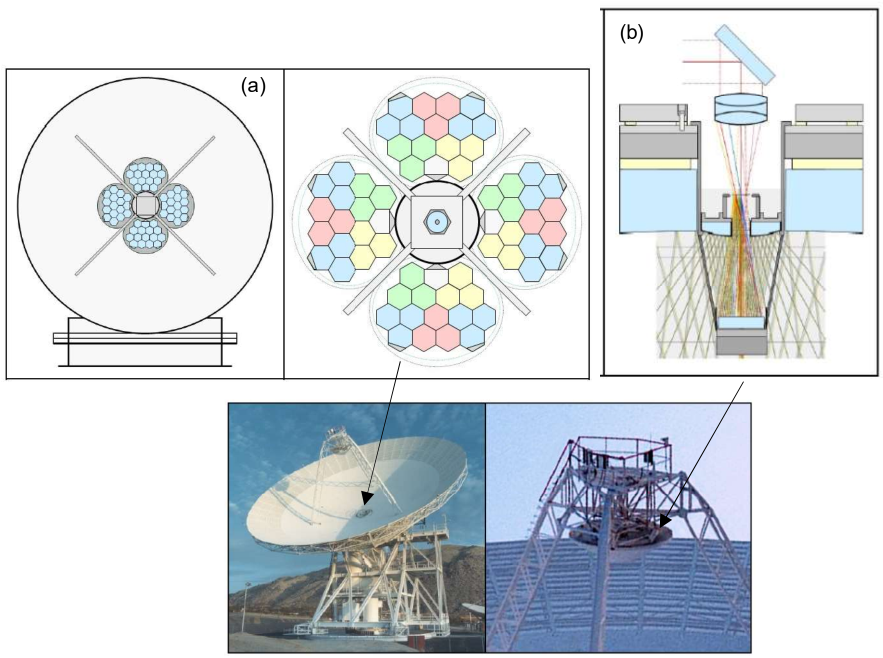
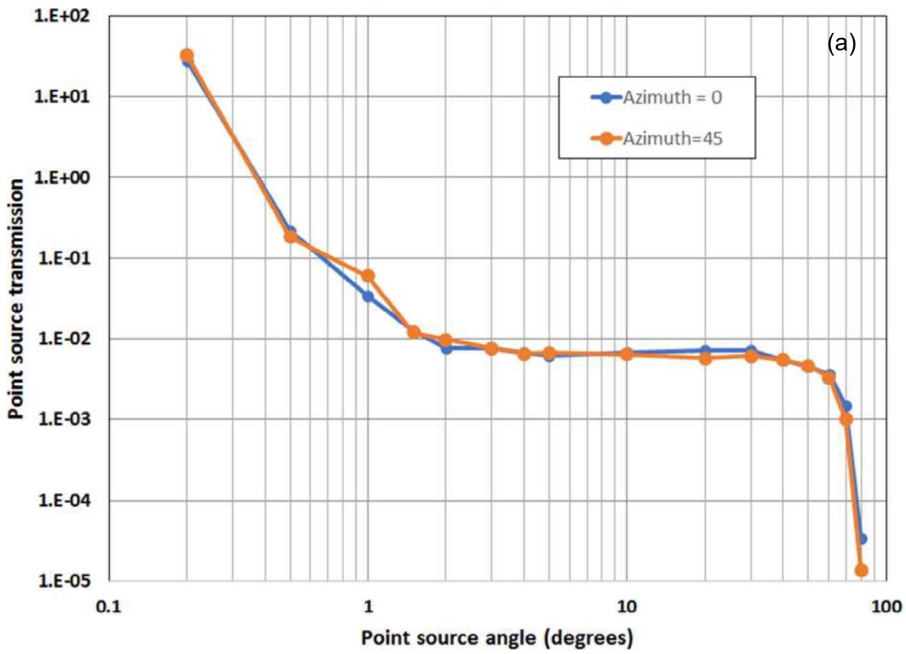


Figure 6. (a) Concept for retrofitting an optical surface to the inner portion of existing 34 m diameter Deep Space Network antennae; (b) secondary aberration corrector (SAC) co-located with the secondary or the RF antenna.

Figure 6 shows a conceptual design of the RF-Optical Hybrid apertures. Four pods of 16 hexagonally close packed mirrors with center separation of approximately 1.2 m provides a collection area equivalent to ~ 8 m diameter. The resulting optical surface is spherical and the collected light is relayed through a spherical aberration corrector (SAC) before bringing the light to a focus beyond which it can be re-collimated and relayed to a communication detector and an acquisition camera. Actuators for beam steering and varying the field of view are also accommodated in the backend optical train. The spherical figure of the segmented primary mirror surface can be maintained using active edge sensors that were developed at JPL for other applications.

The RF-Optical aperture is dome less and protective covers are planned to avoid extended exposure to the elements when not operating. Two key operational questions with the RF-Optical Hybrid aperture concept are the handling of stray light when operating close to the sun and indeed how close to the sun the antenna can be pointed.

Without any mitigation applied the RF-Optical Hybrid antennae would likely support operations while pointed to SEP angles of 10°, since at smaller angles reflected sun light impinges on the RF antenna secondary structure potentially causing thermal damage. The 10° translates to a 65 day outage per Mars synodic cycle (approximately two Earth years). Studies to mitigate this outage are forthcoming.



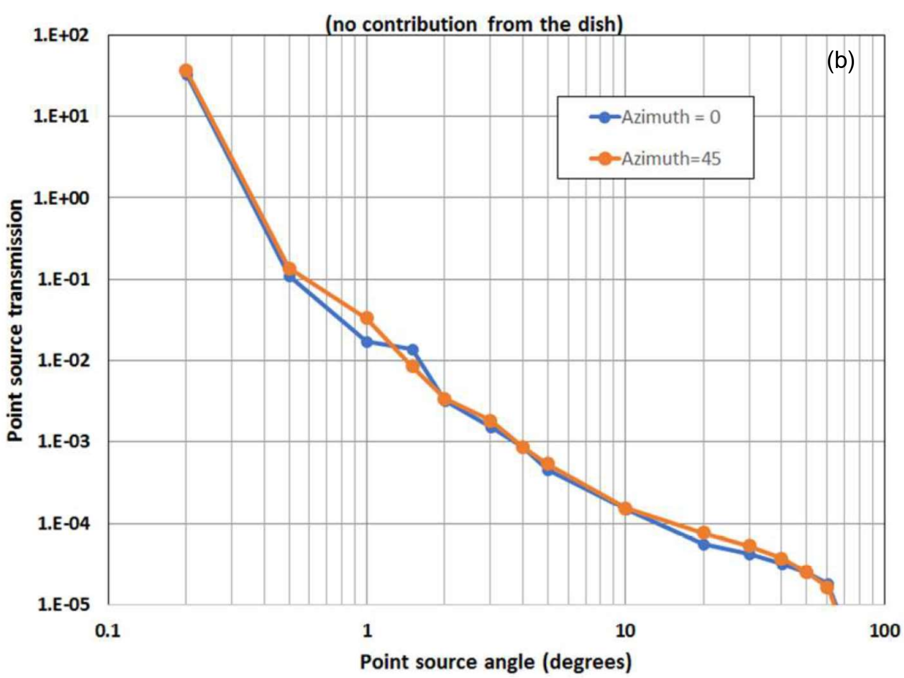


Figure 7. (a) Point source transmission (PST) that includes the portions of the dish versus (b) without the dish surface included.

Initial stray light analysis was conducted assuming a surface cleanliness level of CL 500 a surface roughness of 5 nm and a scratch-dig of 60-40. Providing details of this study is outside the scope of this paper, but the overriding conclusion was that a large contribution of stray light was from areas of the RF dish that was not covered by mirrors (grey shaded) portion in Figure 6a. Figure 7 below summarizes this result.

The point source transmission (PST) is plotted as a function of the sun angle. The PST is defined as the ratio, E_{det}/E_o, where E_{det} and E_o represent stray light irradiance on the detector and entrance aperture. The result indicates that avoiding scatter from the regions of the dish between the mirrors or using a suitably designed Lyot stop results in stray light performance indicated by Figure 7b. Further study on using the Lyot stop indicates that the effective aperture area would be reduced by approximately 75% based on practical limitations of implementing a Lyot stop. If these model based stray light predictions can be verified, the aperture with more realistic cleanliness levels of CL=750 or CL=1000 would provide a reasonable service.

The conclusion from the brief discussion above is that the RF-Optical Hybrid can be utilized for deep-space optical communications down to 10-degree SEP angles. To first order the performance at shallower SEP angles would be representative of a 6m-diameter aperture while at larger SEP angles, to be defined, approximately 8 m of aperture would be available. If implemented, this does provide a path forward in terms of having relatively lower cost ground infrastructure until larger investments are made.

Other future studies related to ground capability are further expanding the SNSPD detector array size that would be needed for use with the larger effective aperture diameters. Means of using some form of adaptive control to reduce the effective field of view in the presence of atmospheric turbulence would recover performance lost to additive background noise and may also allow operating without having to increase SNSPD array area.

5. CONCLUSIONS

In this paper we have reported the status of deep space optical communications at JPL. The DSOC Project is a key activity being pursued in order to implement NASA's first technology demonstration with an emphasis on validating link acquisition/re-acquisition and the high photon-efficiency signaling. Pointers to future development drivers for flight and ground terminals considered critical for advancing the infusion of free-space laser communications were discussed briefly.

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